PARTICLE PHYSICS IN THE HIGH SCHOOL CLASSROOM

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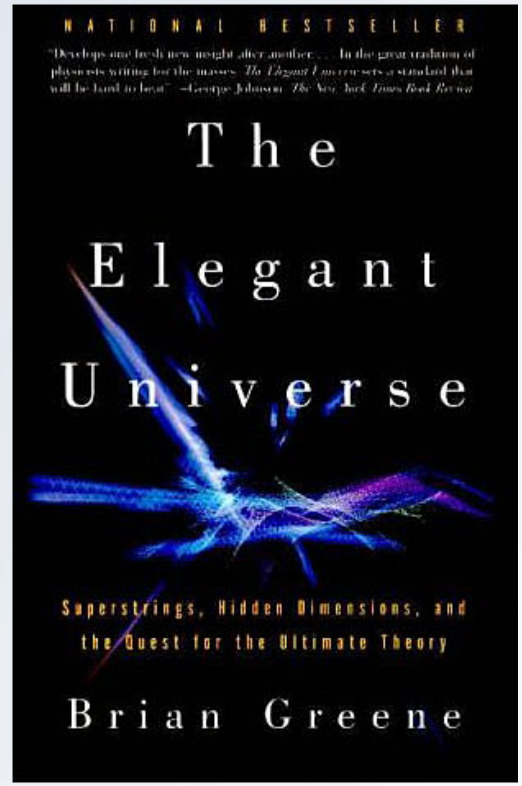
Why particle physics?

- Nothing gets the attention of the public like particle physics
- Practical advances in solid-state physics or material science rarely get the press coverage of particle physics
  - The *New York Times* published 119 articles related to the Higgs boson
  - Graphene, which might actually be useful, has only 33



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Why high school?

- Many students find particle physics fascinating – in some cases (like mine) it convinces them to study physics
- Living next door to Fermilab makes it all the more exciting
- By the time college starts, many students have already chosen a major
- High school is the time to learn about particle physics!

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Success stories

- Modern Physics offered at IMSA as a one-semester class
- Students responded strongly:
  - “I had my mind blown every class”
  - “This is the most interesting class I’ve ever taken”
  - “ModPhys was the highlight of my day”
  - “Before this semester, I hated physics, but now, that hate has subsided and I actually find myself interested enough to pay attention, take notes, do my homework, and look up other resources in my free time.”
- Three students said they decided to become physics majors because of this class

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The problem

- Particle physics is typically taught to physics majors in their junior year – at the earliest
- In the meantime, students study mechanics – arguably the least interesting part of the field of physics

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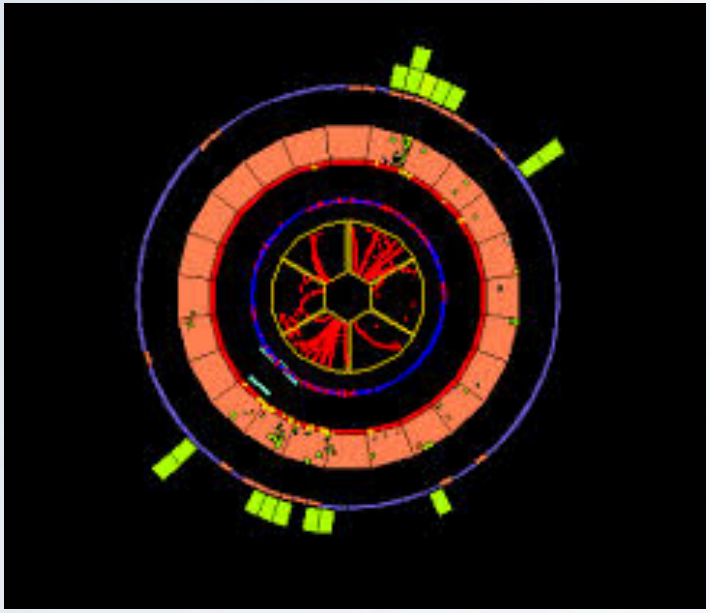
A solution?

- Particle physics theory is very difficult
- Experiment, on the other hand, is relatively easy
  - Often uses fairly simple math
  - Relies on computers
  - Can easily be broken into sections that can be distributed to different students



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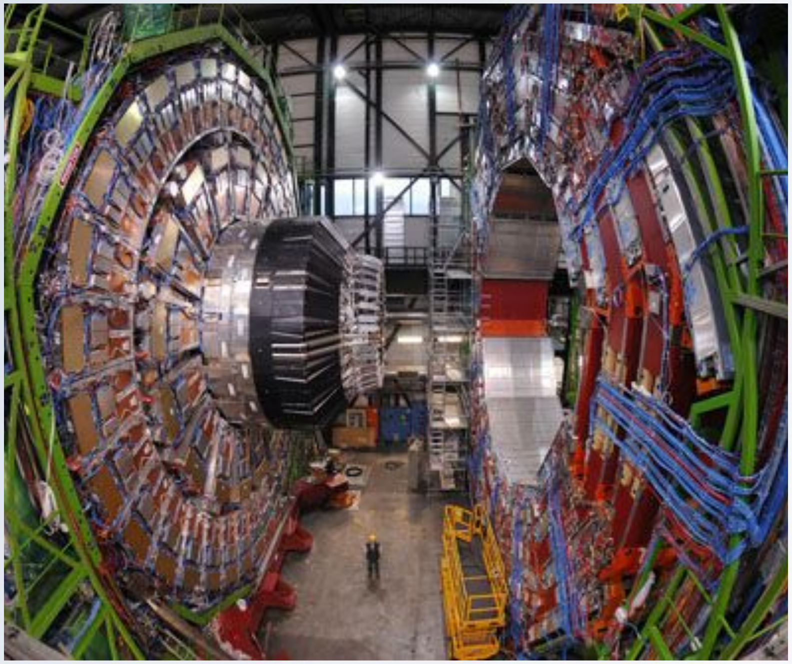
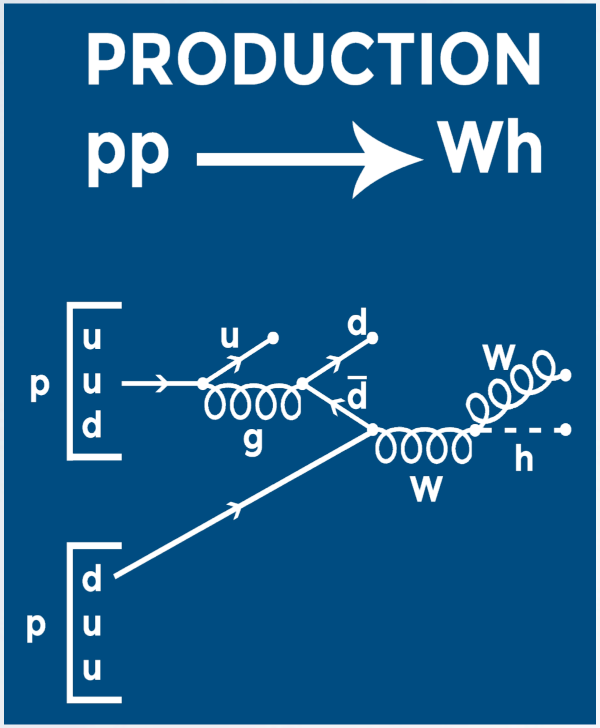
An experiment

- Last semester in Modern Physics, we gave it a try:
  - Found a search for a hypothetical new particle
  - Split the analysis work into twenty parts (one per student)
  - Gave each student simulated data to work with
  - The output of one student's project became the input to the next one



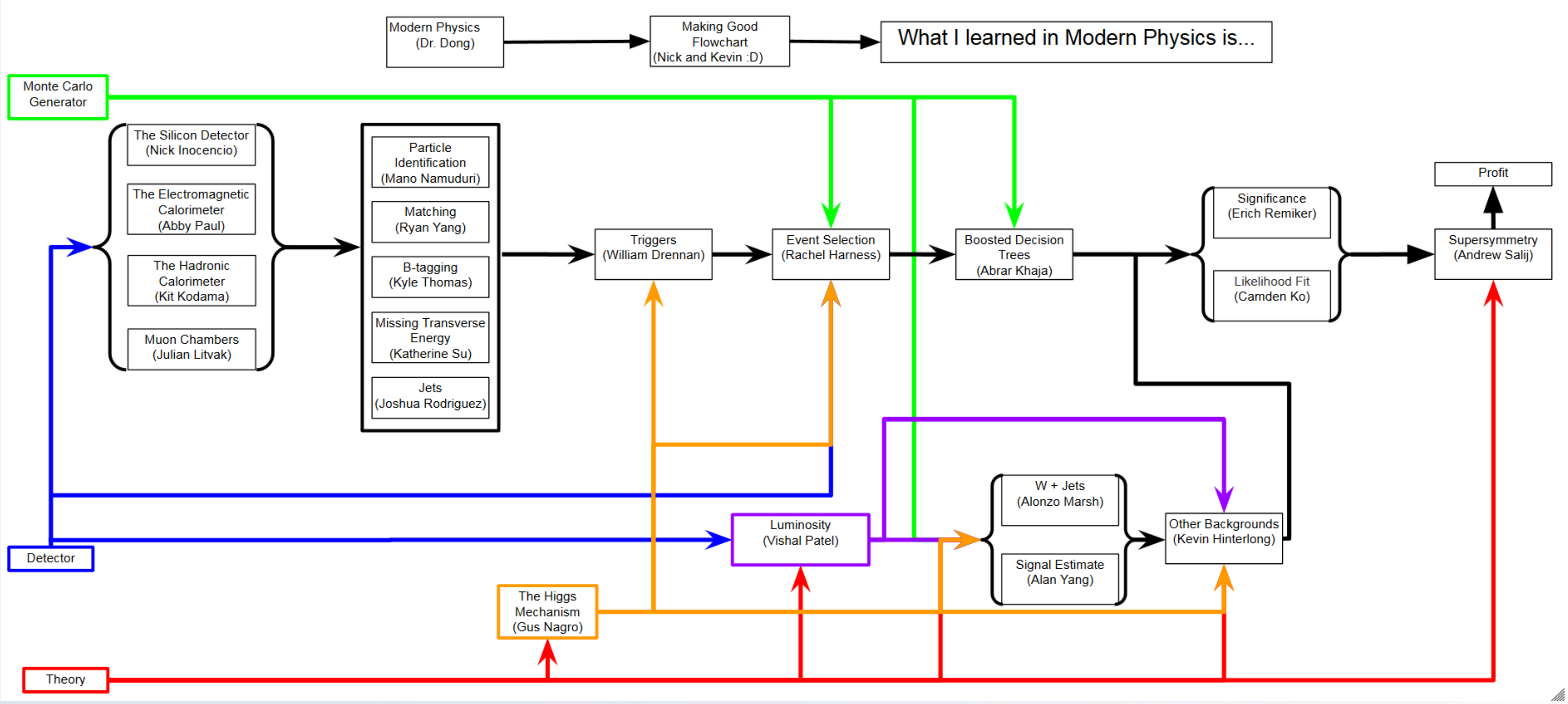
Overview of the project

- Chose a real theoretical about a particle that could be observed at the Large Hadron Collider
- Student projects:
  - Decided what event signature to look for
  - Analyzed raw data from the detector to find objects
  - Identified objects as specific particles
  - Implemented cuts to remove background events
  - Estimated number of events expected
  - Used algorithm to separate signal from background
  - Performed statistical analysis to get result
  - Discussed physical implications of result



Structure of the project

- Students made this chart at the end of the semester



Individual component

- Each student did a short research report about their topic
- Each student had a practice assignment and then a full experimental assignment
- The practice was to prepare for the full assignment, and to allow (ideally) for feedback

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Example: Silicon tracking

- The student got a list of coordinates that represent the positions of "hits" in the detector
- Needed to reconstruct the tracks that particles left behind
- Practice assignment tells students the particle before giving the list of points; the experimental part just gives a list of points

0.0364344	-0.0246674	0.171373
0.0336382	-0.0283578	0.171125
0.0335477	-0.0284649	0.17148
0.0327986	-0.0293214	0.173209
0.028479	-0.0335235	0.173065
0.0302559	-0.0319323	0.173441
0.0293162	-0.0327948	0.173957
0.0277505	-0.0341309	0.173683
0.0279145	-0.0339957	0.173999
0.0283587	-0.0336272	0.174121
0.0282446	-0.0337243	0.174668
0.0288457	-0.0332124	0.174982
0.0297274	-0.0324271	0.175506
0.0287779	-0.0332718	0.17534
0.0267055	-0.0349543	0.174661
0.0280657	-0.0338715	0.173926
0.0287084	-0.0333335	0.17577
0.0295837	-0.0325582	0.175594
0.0288432	-0.0332175	0.17593
0.02776	-0.034129	0.176314
0.0276834	-0.0341898	0.175914
0.033016	-0.0290774	0.17344
0.0273862	-0.0344283	0.17589
0.0240946	-0.0368114	0.175906
0.0265454	-0.0350794	0.17561
0.0245463	-0.0365137	0.176308
0.0277944	-0.0340955	0.174733
0.0431602	-0.00855532	0.0712602
0.0206159	-0.0388533	0.177807
0.0273811	-0.0344308	0.175142
0.0346987	-0.0270522	0.172347
0.0355217	-0.0259641	0.170318
0.0190099	-0.0396521	0.178956
0.0146369	-0.0414494	0.179889
0.0222898	-0.0379218	0.17809
0.00753173	-0.0433242	0.182479
0.0273336	-0.0344683	0.175301
0.0219052	-0.0381577	0.209017
0.0275454	-0.0343007	0.175909
0.0210383	-0.0386424	0.210891
0.0270159	-0.0347215	0.211445
0.0260408	-0.0354597	0.211879
0.0261634	-0.0353694	0.212498

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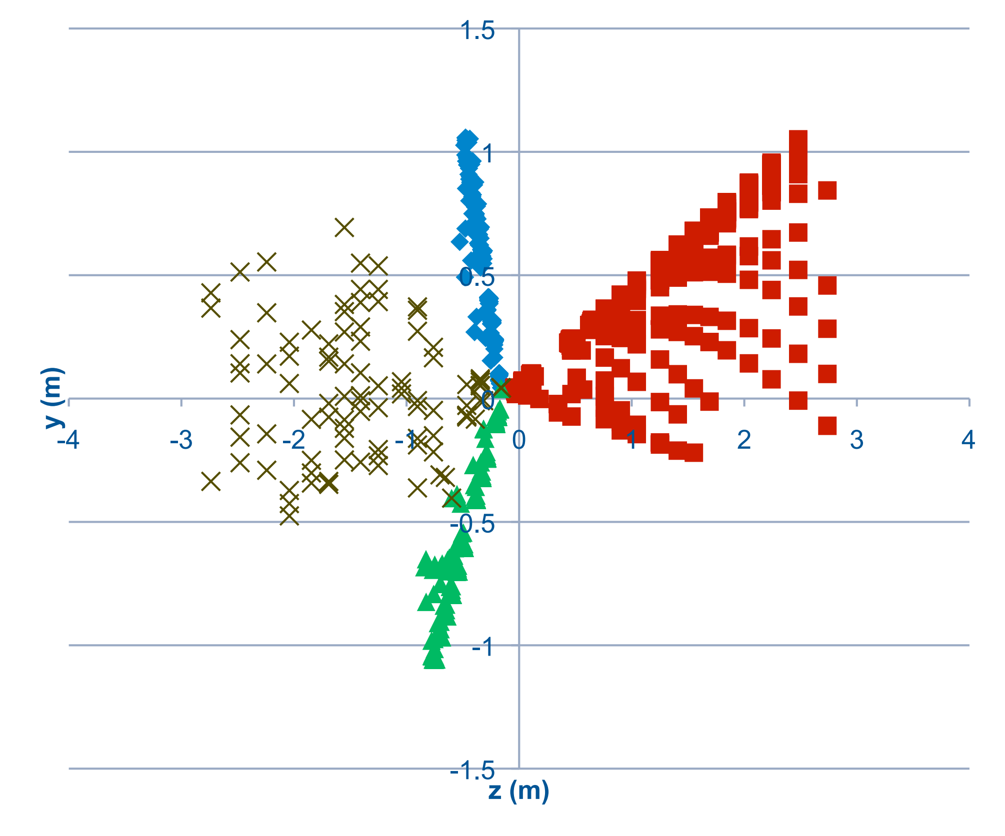
Silicon tracking results

- Here is one plot the student generated, showing two tracks and two jets in an event



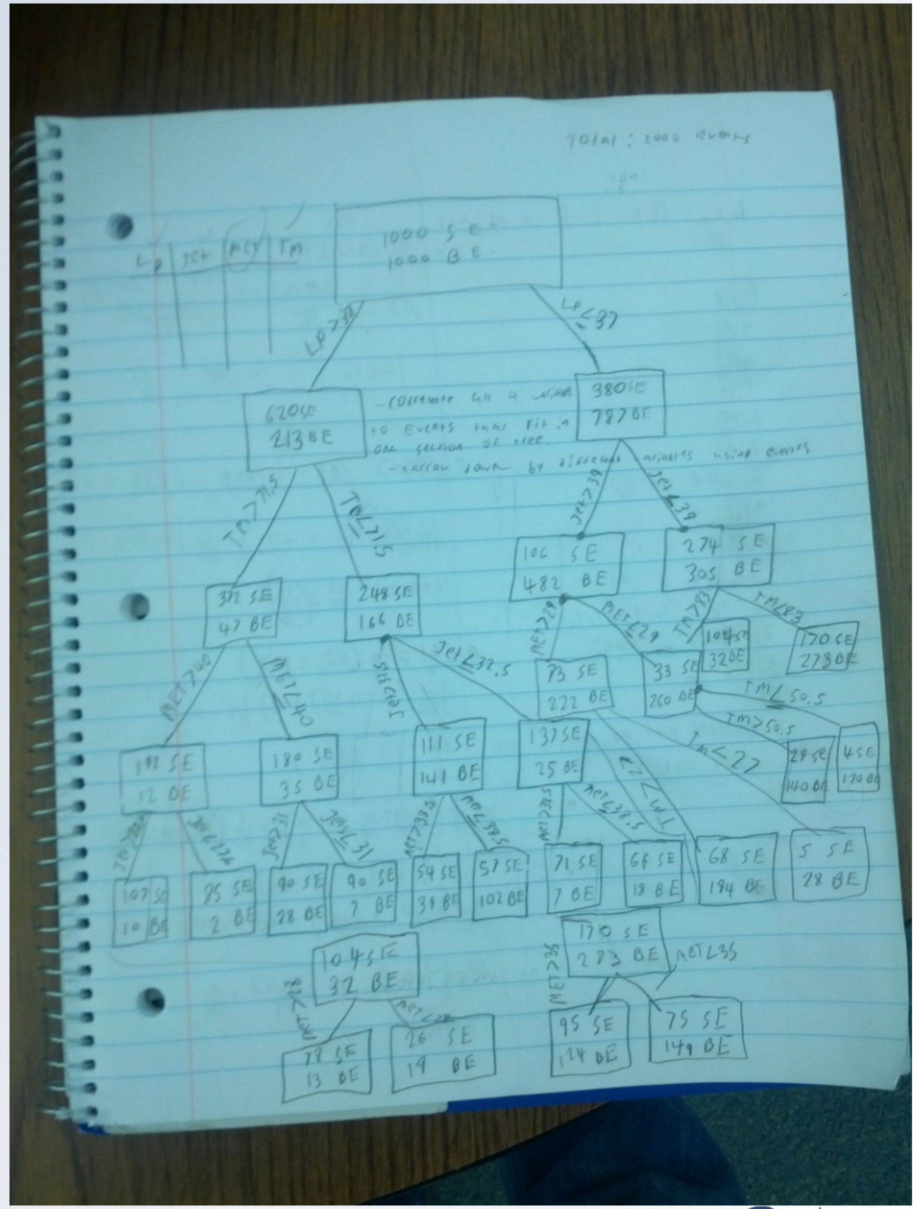
Example: Decision trees

- The student got a list of variables for simulated events of signal and background
- The student's job was to design a sorting algorithm (a decision tree) that separated signal from background

Event	Lepton pT	Leading je	MET	Transverse mass
0	27.3515	46.0681	25.3077	35.3931
1	16.9689	54.6297	16.9585	10.8129
2	25.4933	30.5002	35.7108	7.38512
3	20.8207	54.7628	11.803	51.4768
4	16.2869	51.6151	36.266	27.0023
5	37.8064	62.3784	69.3532	54.8898
6	34.0762	32.3852	46.4658	83.7788
7	56.0569	53.7849	16.0636	58.7567
8	28.3897	50.0958	30.9811	46.822
9	4.10087	40.2504	7.95908	51.0093
10	28.1695	28.7536	69.8698	37.5506
11	20.2254	44.7512	57.1025	37.2845
12	26.2893	23.6708	20.7378	41.54
13	32.5253	50.8955	9.51241	0.376926
14	15.779	63.8804	28.3168	56.6985
15	28.5063	65.7441	59.1395	107.887
16	14.8949	48.0953	25.5705	66.3328
17	45.0948	30.2783	25.3903	74.8869
18	35.4146	45.0007	7.90181	66.1468
19	30.111	22.3482	4.23016	14.9467
20	26.9254	32.2729	60.4015	61.8885
21	43.12	15.558	26.465	11.3084
22	31.8799	38.1324	53.7541	43.4093
23	43.3586	61.5905	31.025	20.4967
24	14.4775	52.3862	48.8673	74.4666
25	25.7967	45.0473	42.6957	94.4891
26	45.865	19.3893	35.462	37.763
27	28.8636	35.8462	10.1986	86.4899
28	2.21329	45.16	8.22032	15.3478
29	38.2589	60.375	41.6169	67.1541
30	14.2142	33.611	42.5554	21.1909
31	15.1972	66.5446	17.881	34.7723
32	32.159	41.7649	72.4289	40.7037
33	39.8779	44.0681	30.8389	88.999
34	29.9388	40.2509	5.43577	75.4554
35	38.6616	63.2147	9.02922	107.502
36	30.9919	31.8215	29.2476	45.682
37	29.6684	40.9736	31.8634	57.9897
38	35.6807	34.3335	25.6858	98.5605
39	40.9439	34.8848	49.6519	83.0112
40	36.3683	25.8295	58.6908	27.2233

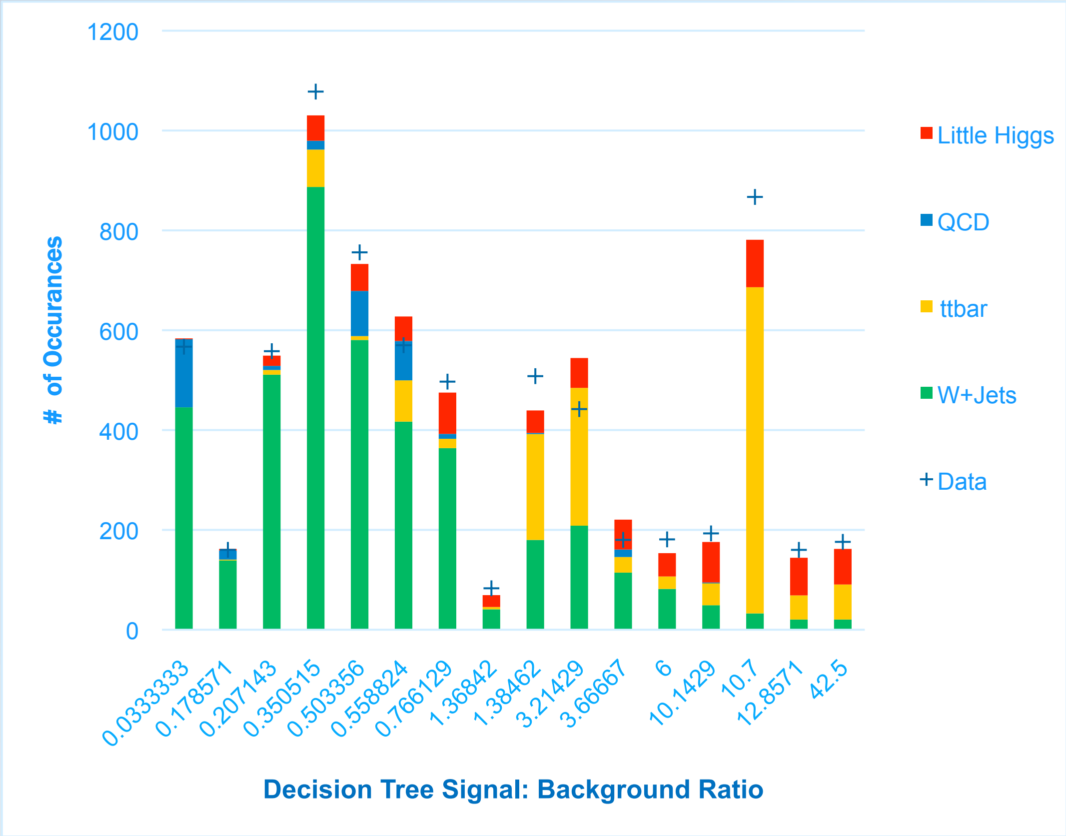
Decision tree

- Here is the decision tree the student made (by hand) using Excel to sort the events



Decision tree results

- The decision tree could then be applied to all the data to make this chart



The result

- Students put their project together into a presentation which they gave to a physicists at Fermilab
- http://youtu.be/z3rXFfeyIzc
- Very positive comments from students:
  - “Seeing the scientific process in action”
  - “Able to see particle physics actually being experimented and how it is done”
  - “Allowed me to relate what I learned somewhat to the real world”
  - “Required students to know all about their part in the project”
  - “Really taught me how much we had accomplished as a class”

Can this work at other schools?

- IMSA is an unusual environment, and Modern Physics is an unusual class
- On the other hand, most teachers have high-achieving students who may be interested in this material
- Could this be an individual project for an interested student, or a class activity for an advanced class?

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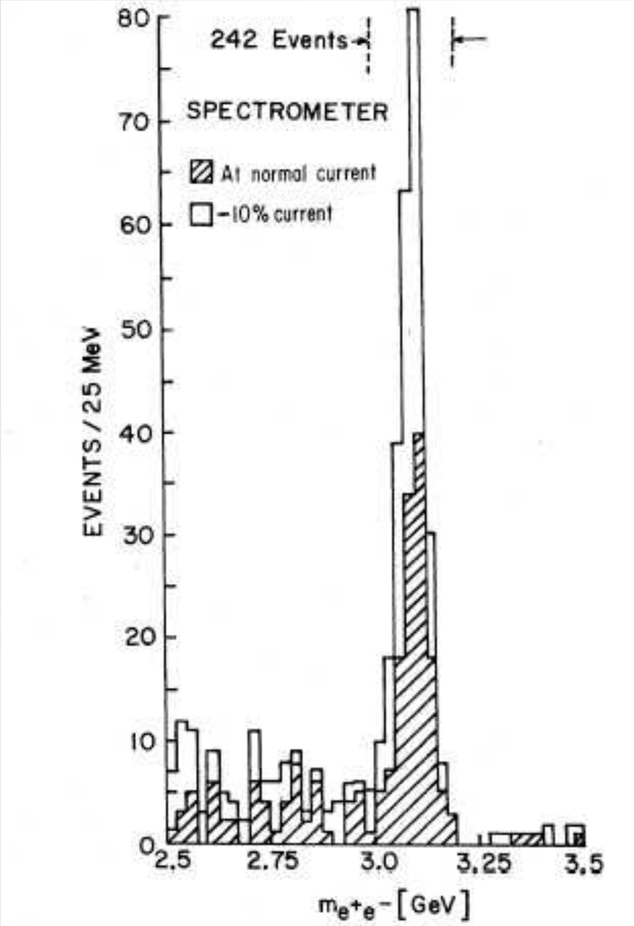
Obstacles

- Time (other topics need to be covered)
- Motivation (not in the NGSS)
- Expertise (not everyone is a particle physicist)
  - The Internet is a helpful resource, but unfortunately not great for particle physics
  - I have developed some materials to help with this

The J/ψ particle

- Discovered in 1974
- Confirmed the quark model of physics
- Some historical details given in http://arxiv.org/pdf/hep-ph/9910468v1.pdf
- If you have the right equipment, it is relatively easy to find



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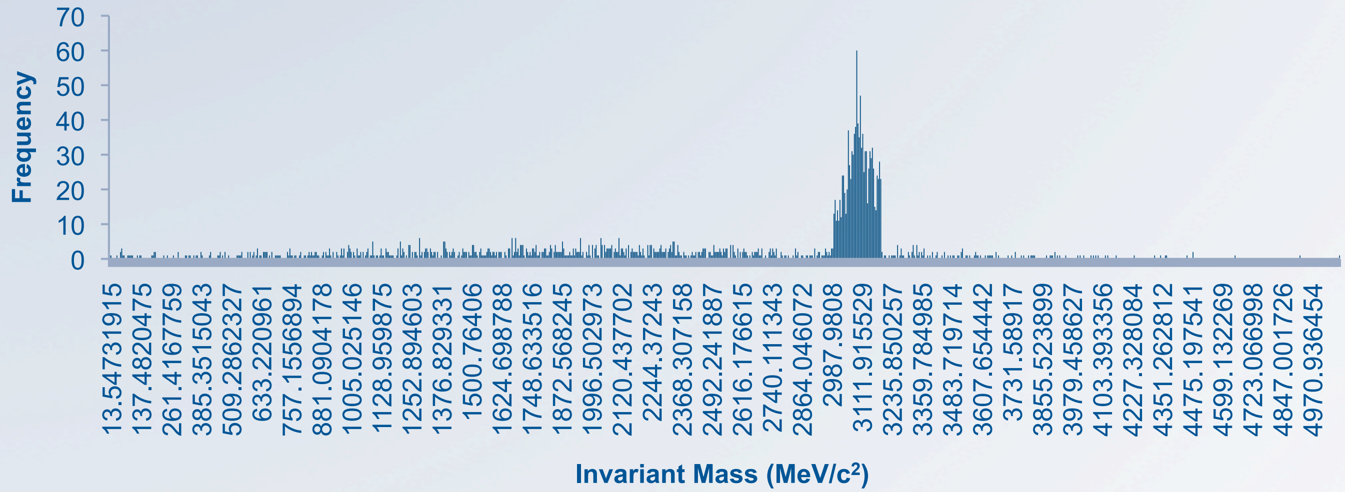
Project

- I have prepared a list of 2000 (simulated) events from a hadron fixed-target experiment
- Each event identifies an electron-positron pair from an event and gives the energy and momentum of each
- Looking at any of the variables does not reveal anything interesting

Event	Energy (MeV)	Momentum-x(MeV/c)	Momentum-y(MeV/c)	Momentum-z(MeV/c)	Ene
0	600.451	304.084	-240.709	-458.403	
1	1081.06	54.7884	803.171	721.525	
2	2070.32	-1816.8	790.848	599.998	
3	2925.45	-417.196	2007.92	2086.26	
4	604.733	56.0373	294.19	525.371	
5	383.122	-366.8	35.9719	-104.626	
6	3438.58	-2503.45	711.41	2247.32	
7	3809.41	-2641.55	2736.13	-217.761	
8	1727.59	-744.28	-1471.79	514.234	
9	623.476	-422.027	-329.928	319.004	
10	4653.28	604.034	2121.13	4097.43	
11	188.526	-150.095	7.45164	113.832	
12	1677.34	721.249	248.489	1493.83	
13	3091.87	546.14	2626.95	1536.39	
14	2620.12	-281.256	-1139.89	2342.35	
15	485.665	-385.747	-4.90826	295.034	
16	1749.93	-613.43	420.695	1583.98	
17	2371.66	1023.21	917.472	1932.89	
18	1734.73	384.834	-211.954	1678.18	
19	222.588	3.75063	120.843	-186.891	
20	1733.13	1730.09	83.8109	-59.2175	
21	722.553	-80.5614	-595.121	-401.777	
22	1204.29	-385.411	-563.983	991.813	
23	2826.75	-122.733	-819.454	2702.59	
24	5405.8	1262.11	2342.33	4705.66	
25	179.939	83.8107	77.4116	-139.145	
26	1458.4	855.359	556.623	-1041.86	

Invariant mass

- Students can then learn about the concept of invariant mass, using supplemental reading from the Internet
- If they calculate the invariant mass (using Excel) for each event, they might start to see a pattern
- If they make a histogram of the data, they should be able to see the signature of the new particle



Material

- I have provided a student version and a teacher's version
- The student version is intended to incite students to research more, in books and on the Internet, to understand key terms
- The teacher's version is intended to be used to give hints to stuck students
- Let me know how it goes!